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Neutronics performance and activation calculation of dense tungsten granular target for China-ADS

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ABSTRACT

Spallation target, which constitutes the physical and functional interface between the high power accelerator and the subcritical core, is one of the most important components in Accelerator Driven Subcritical System (ADS). In this paper, we investigated the neutronics performance, the radiation damage and the activation of dense tungsten granular flow spallation target by using the Monte Carlo programs GMT and FLUKA at the proton energy of 250 MeV with a beam current of 10 mA. First, the leaking neutron yield, leaking neutron energy spectrum and laterally leaking neutron distribution at several time nodes and with different target parameters are explored. After that, the displacement per atom (DPA) and the helium/hydrogen production for tungsten grains and structural materials with stainless steel 316L are estimated. Finally, the radioactivity, residual dose rate and afterheat of granular target are presented. Results indicate that granule diameter below 1 cm and the beam profile diameter have negligible impact on neutronics performance, while the target diameter and volume fraction of grain have notable influence. The maximum DPA for target vessel (beam tube) is about 1.0 (1.6) DPA/year in bare target, and increased to 2.6 (2.8) DPA/year in fission environment. Average DPA for tungsten grains is relatively low. The decline rate of radioactivity and afterheat with cooling time grows with the decrease of the irradiation time.

1. Introduction

In recent years, the Accelerator Driven Subcritical System (ADS) has been proposed as one promising option for transmutation of the highly radioactive nuclear waste. Spallation target, which constitutes the physical and functional interface between the high-power accelerator and the subcritical core, is one of the most important components in ADS facility [1–3], where high energy protons are impinged on target material to produce neutrons. These neutrons are multiplied in a sub-critical core to transmute minor actinides and long-lived fission products. In China, a long-term program 'future advanced fission energy-ADS transmutation system' was launched as a strategic leading science and technology program in January 2011. There are three phases for this program: the first stage is principle verification, the aim of which is to solve key technological problems of the accelerator, spallation target, and subcritical core; the second stage is demonstration facility building; the last is the industrial facility and full-size technological integration [4]. According to the China-ADS roadmap parameters, 250 MeV beam energy will be realized with an expected completion time near 2022 [5].

In order to attain a high neutron flux in spallation target, MW-scale proton accelerator is required for transmutation demonstration [6], which will lead to many technical challenges in building target station. The first issue is how to remove the heat from the high-intensity proton beam deposited in the target. The second key issue is the lifetime of the target, which is limited by radiation damage, heat shock, corrosion, etc. At present, there are various kinds of targets that have been designed, constructed, and operated, for example the plate targets in KENS, IPNS, ISIS and CSNS [7,8]; rod targets in SINQ at PSI [9]; heavy liquid metal targets with a beam window in SNS, JSNS and MEGAPIE [10–12]; heavy liquid metal target without a beam window in MYRRHA project [13]; and rotating targets in European ESS project [14], German SNQ project [15], 2nd target station of SNS and for the Chinese CSNS project [16]. Following the various spallation targets above, a gravity-driven Dense Granular Target (DGT) has been proposed lately [4]. In the DGT proposal, the flowing tungsten grains are adopted as the target material, which can bring the thermal power

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out of the beam-target interaction region, and both the gravity and electromagnetic/mechanical lifting appliance can provide impetus for the granular target to form a loop movement.

For the first stage, the China-ADS project proposed to build a test facility at the proton energy of 250 MeV with the beam current of 10 mA. In this work, the neutronics performance, the radiation damage and the activation of dense tungsten granular flow spallation target at 250 MeV proton energy are explored. First, we investigate the neutronics performance of flowing granular target at several time nodes and with different granular size in our target configuration. Then, the effects of target vessel diameter, beam profile diameter and volume fraction of grain are explored. Furthermore, the radiation damage of the tungsten granular target and the structural materials are estimated for the bare target and coupling target with subcritical blanket. Finally, the radioactivity and afterheat in the two cases are discussed.

2. Calculation model

As shown in Fig. 1, the circulation system of DGT consists of a granular flow hopper, a heat exchanger, a grain filter & storage and a grains elevator. These constituents guarantee a safe and normal circulation of the working medium in the entire system. In granular flow hopper, the tungsten grains flow into the spallation region under gravity from the upper annular duct with a coaxial beam tube inside. Then the 250 MeV, 10 mA proton beam that is uniform in distribution from a high-energy linear particle accelerator interacts with the flowing grains below the beam tube. The grains will pass through the spallation region quickly and will be discharged from the orifice of the hopper to avoid being melted down. The whole granular flow target is about 8 m in height, while the range of the 250 MeV protons in tungsten is less than 10 cm. Therefore, in the following investigation we just take the main effective parts of the spallation target with a simplified geometry model as shown in Fig. 2. In this geometry model, the coaxial beam tube inside the target hopper is 15 cm in inner diameter, 50 cm in height and 0.5 cm in thickness. The target hopper is 35 cm in inner diameter, 150 cm in length and 0.5 cm in thickness. The material of vessels is adopted as stainless steel 316L. Beyond this scope (0–150 cm) of the target in Fig. 2, the neutron flux decreases by two or three orders of magnitude. Therefore, in this paper we neglect the effects of the relevant neutron flux. In the grains calculation, the spatial distribution of the random grains are generated by using the discrete element method (DEM) [17–19]. A static tungsten grains are randomly filled into the unoccupied spaces within the target hopper and out of the beam tube, with the average volume fraction of about 0.6. In the homogeneous simulation, we use the same target size as the granular target, but make approximation in two aspects, that is, the dependence of the equivalent tungsten density on volume fraction and a semi-spherical surface formation due to the flowing of granular materials under the end of beam tube are supposed.

In order to survey the neutronics performance of the granular target, our group have developed a GPU-based Monte Carlo particle transport program GMT [20], which is based on the Intra-nuclear Cascade of Liege (INCL4.6) model [21] and the ABLA evaporation/-fission model [22]. The INCL4.6-ABLA model has an overall good agreement with the experiment results in a wide range. At neutron energies below 20 MeV, the evaluated data library ENDF/B-VII.1 [23] is used for accurate simulation of low energy neutron trans-

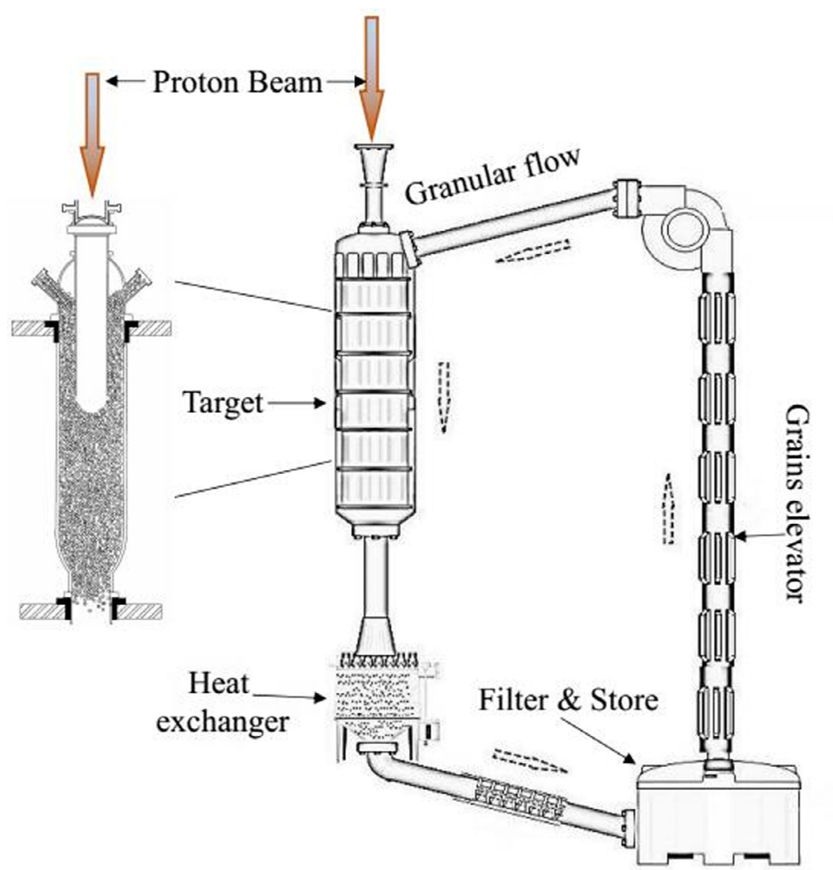

Fig. 1. Schematic design of a gravity-driven dense granular target system.